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REQUIREMENTS OF ENGINE DYNAMICS IMPLIED BY THE THRUST MODULATION CONTROL FOR VTOL AIRCRAFT

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H. G. Offenbeck(1)

ABSTRACT. In the design of V/STOL high performance aircraft, the choice of the engines and the control systems plays an important role for gliding and transition flight. For the control system, and the choice of engine for thrust modulation control, there are three dynamic criteria: a) stabilization for small disturbances; b) stabilization for engine failure; c) control behavior.

In the design of high-performance V/STOL aircraft, selection of the engines and control systems plays a dominant role in hovering and transition flight. It considerably affects the weight and cost balance, and the profitability of a VTOL aircraft.

The engine dynamics is an important criterion in selection of the engine. This is certainly the case in the use of engines alone for production of lift without active function. Pitch, roll, and yaw control requires dynamic behavior which is not provided by conventional jet engines. Extensive parametric studies for VTOL fighter-bombers have shown that it is desirable to make use of the engine for torque production, because with supplemental use of the engine for direct torque production about the pitch and roll axes, the size can be reduced by as much as 10%, and the aircraft weight up to 18%. These results were presented by Mr. Kazan and Mr. Krause at the 5th Aerospace

*Numbers in the margin indicate pagination in the original foreign text.

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Science Meeting under the title "A Comparative Analysis of the Effect of the Hover Control Concept on V/STOL Aircraft Size". By use of the engine as a torque control element, the engine is drawn into the control loop.

For the control design, and with thrust modulation control, there are three dynamic criteria for engine selection:

1. Stabilization for small disturbances
2. Stabilization in case of engine failure, and
3. Control behavior.

The requirement for attitude control and stabilization about the pitch and roll axes necessarily arises from the requirement that vertical take-offs and landings must be performed with the reliability of a category II instrument landing, on a landing area of 4 aircraft lengths and two aircraft wingspan widths, with ground visibility of one-fourth nautical mile, cloud height of 100 m above the ground, a wind of 30 knots and gusts with a mean velocity of 3 m/sec RMS.

Thus, the control system should be designed so that the small disturbances such as gusts or engine asymmetries can be controlled below the pilot's threshold of perception, i.e., below 3 to 4 degrees of attitude deviation. In order to hold the expense for stabilization within defensible limits, the engines should show a linear characteristic in the stabilization range, which can be described by the transfer function $\frac{1 + T s}{1 + \frac{2\varphi}{\omega} s + \frac{1}{\omega^2} s^2}$. The usefulness of the engines for stabilization is plotted in Diagram 1 by parameter combinations. For geometrically similar aircraft configurations with the same wing loading, the gust disturbances, and thus the thrust changes for controlling them out, are a function of the aircraft weight. The dependence is plotted for the pitch and roll axes in Diagram 2. From this dependence and the thrust geometry at the moment, the thrust changes needed for stabilization of small disturbances can be calculated.

Compensation for engine failure is another critical point for engine and control system dynamics. For the failure of the critical engine, the requirement is established that the maximum deviation in position shall be not greater than 35 degrees, and the final deviation, which is to be reached after 3 to 4 seconds at the latest, shall not be greater than 10 degrees. In this way the capability for saving the pilots is guaranteed.

The thrust changes needed for compensation of engine failure can no longer be represented dynamically by a linear system. Therefore, a non-linear model was produced for this analysis of engine failure. Its characteristic curve is determined by two parameters. This model has about the same dynamics as the engine. Parameter A represents the mass dynamics of the engine, and parameter B the additional thrust from momentary temperature increase in the combustion chamber (Diagram 3). The requirements on the engine in case of engine failure are now very closely linked with the dynamics of engine failure and the idling thrust of the engine remaining for control. The thrust curves for three different engine failures are plotted in Diagram 4. Failures 1 and 2 show a time course such as results from sudden cutoff of the fuel supply. Time course 3 shows a progressive failure; but a failure of this type will not really happen.

As a result, note the maximum angular deflection for the various engine failures as a function of engine parameter B. The second limiting curve (final deflection less than 10 degrees) is also plotted.

Diagram 5 shows the effect of the idling thrust. There are still other quantities, such as different pairs of engines or different dynamics for thrust increase and thrust reduction, but in our study they were second-order quantities. For judgement of control behavior by the pilot, four quantities are decisive:

1. the assignment of deflection force to control deflections
2. control deflection for attitude change, as well as the time and course of attitude change.

Diagram 7 shows a time course of attitude change such as is desired for a step change of control. The characteristic quantities are the one-time overshoot of 7% at most, which for a second-order system corresponds to a damping of 0.6 or 0.7, as well as the time TC which is needed to reach 95% of the final value.

It has been shown that the damping enters very strongly into the pilot's judgement, so that the optimum value was established as a requirement.

Diagrams 8 and 9 show the pilots' judgement on the control effectiveness and the time constants TC about the pitch and roll axes. The Cooper scale was used as the evaluation scale. The results come from simulation studies on the fixed-base 3-axis rotor and the 6-degrees-of-freedom simulator, as well as from flight tests. For the pitch axis, the best control behavior results with a time constant of 0.4 to 1.5 second and a steering effectiveness of 2.9 degrees per inch. The time constant TC is approximately the same for the roll axis. The optimum for control effectiveness is at 3.4 degrees attitude change per inch control deflection. In order to transform this value into requirements for the torque-adjusting element, the adjusting element dynamics were approximated by a first-order delay with boundaries.

Diagram 10 shows the relation between the time constants TC, and the angular acceleration per attitude deviation for various torque adjusting element time constants TT. As is to be expected, when TC is decreased the angular acceleration must be increased for constant DT and constant attitude change. Likewise, increase of the time constant DT causes an increase of the angular acceleration.

All these factors, control behavior, disturbance behavior, and engine failure, must be considered in the selection of an engine. Together they yield the engine specification.

They are also decisive for the capability to carry out a project. For vertical or short take-off aircraft with thrust modulation , they are more important than the thrust-weight ratio.

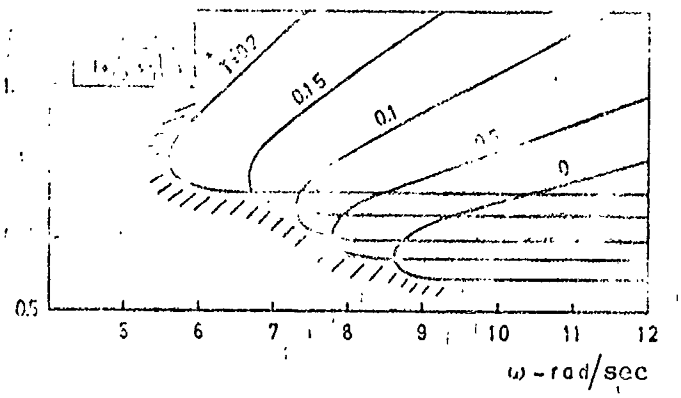
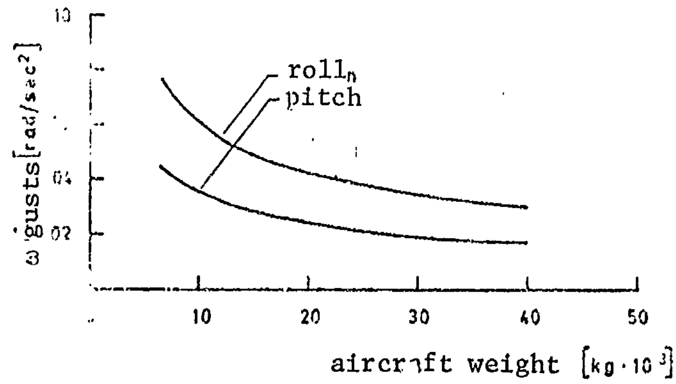


Diagram 1.

Diagram 2.



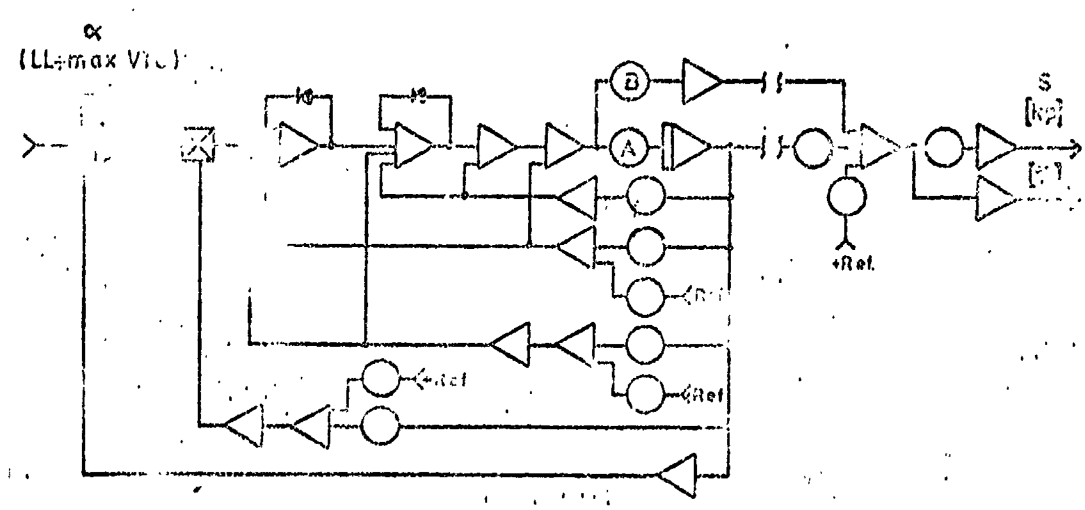


Diagram 3.

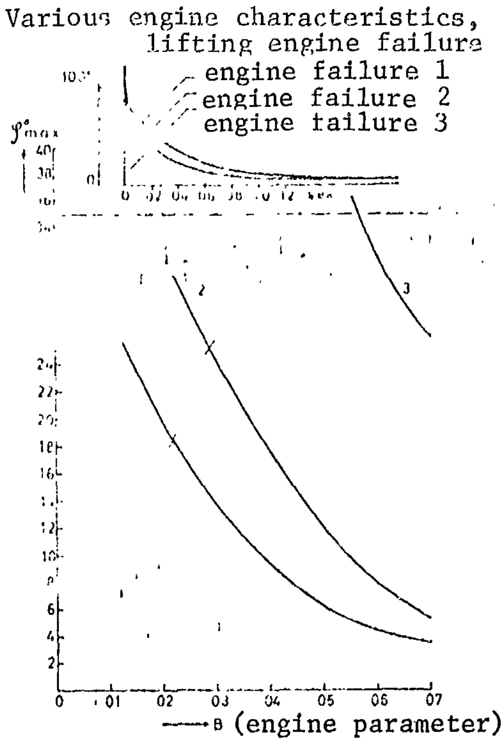


Diagram 4.

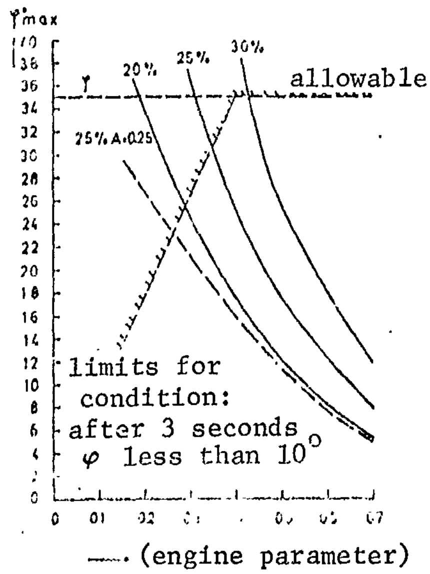


Diagram 5.

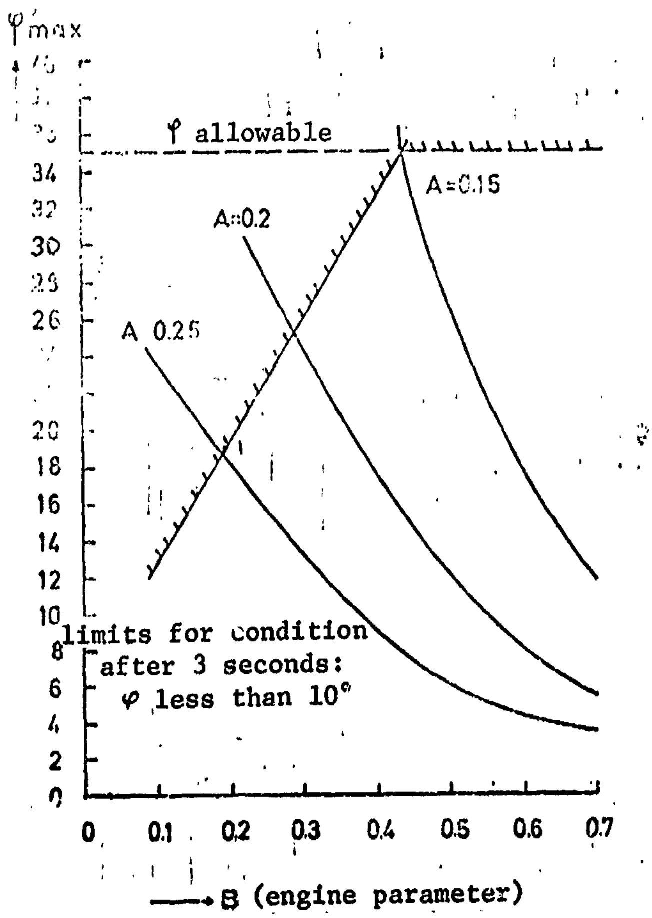


Diagram 6.

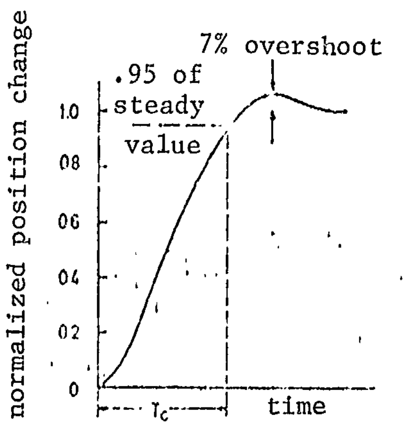


Diagram 7.

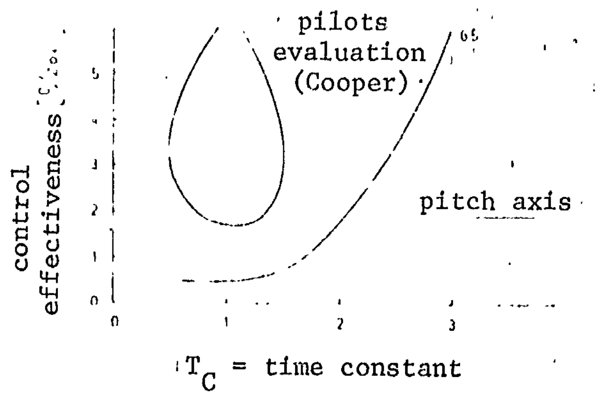


Diagram 8.

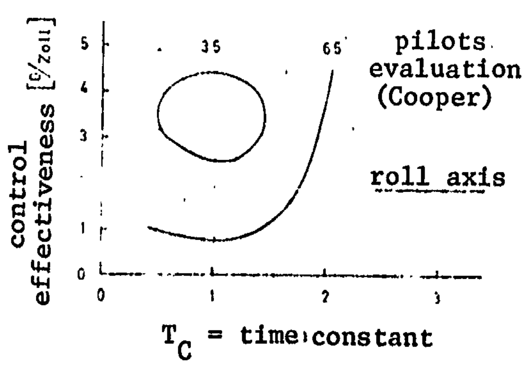


Diagram 9.

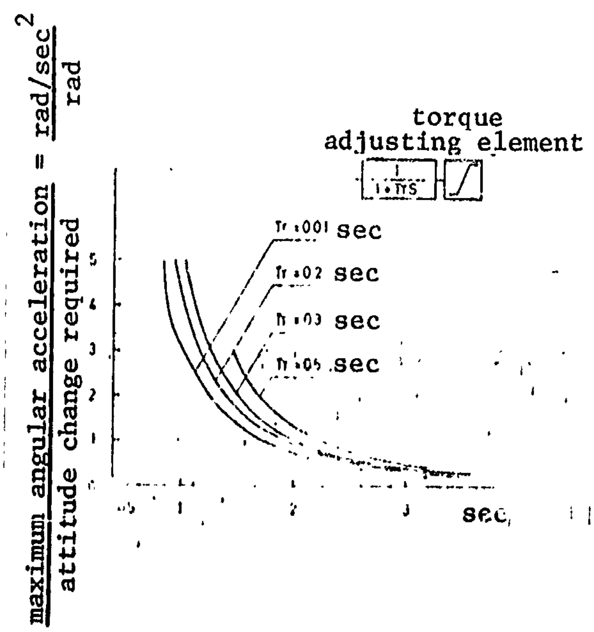


Diagram 10.

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